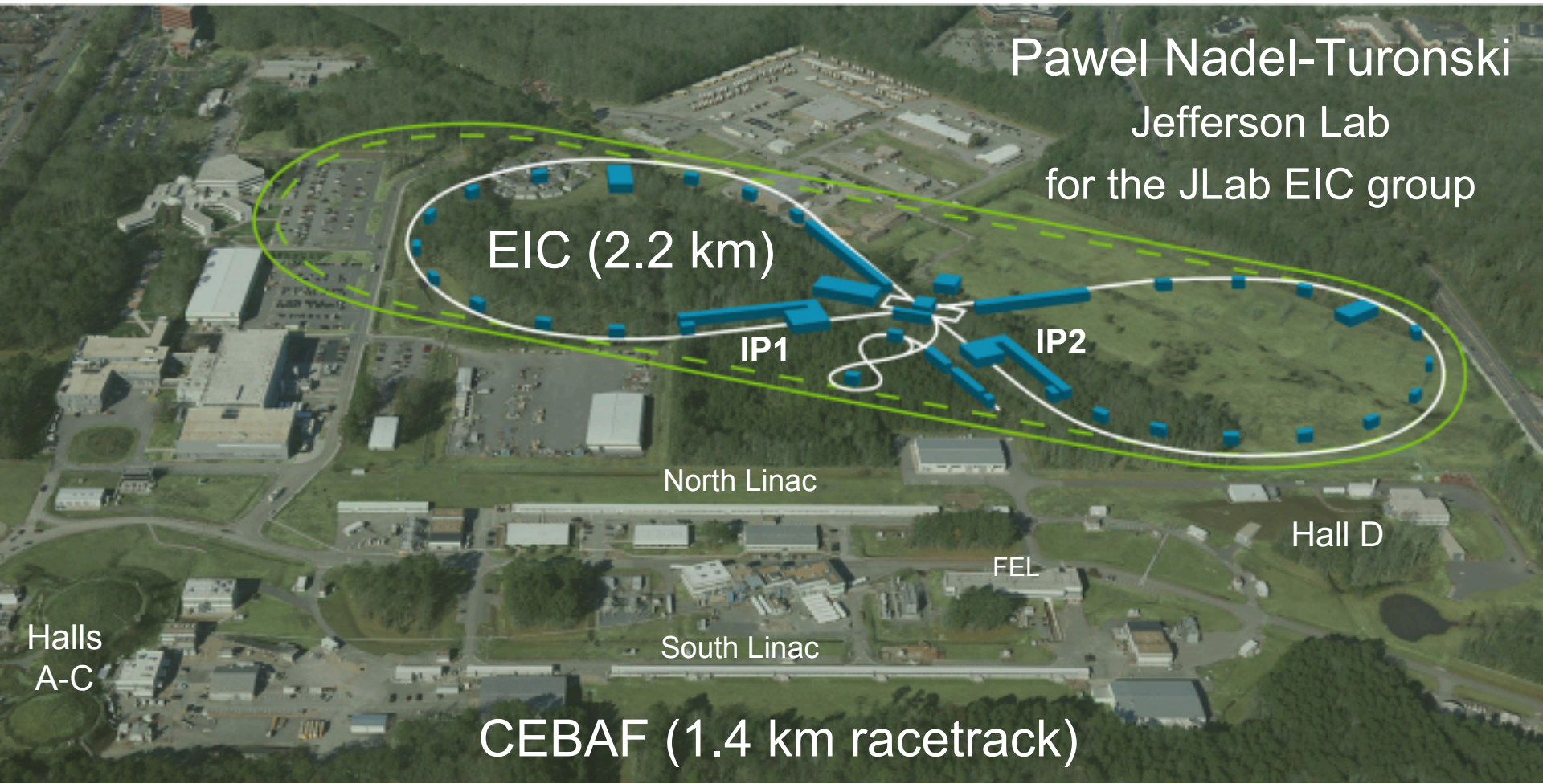


JLab EIC full-acceptance detector

Pawel Nadel-Turonski
Jefferson Lab
for the JLab EIC group



Outline

- Introduction
- Extended interaction region and detector integration
- Forward hadron spectrometer
 - Small-angle detection of hadrons and nuclear fragments
- Central detector
 - Layout and subsystems
- Integrated small-angle electron detection
 - Compton polarimeter, low- Q^2 tagger, luminosity monitor
- Bunch identification and asynchronous triggering at high rep rates

A detector for the EIC science program

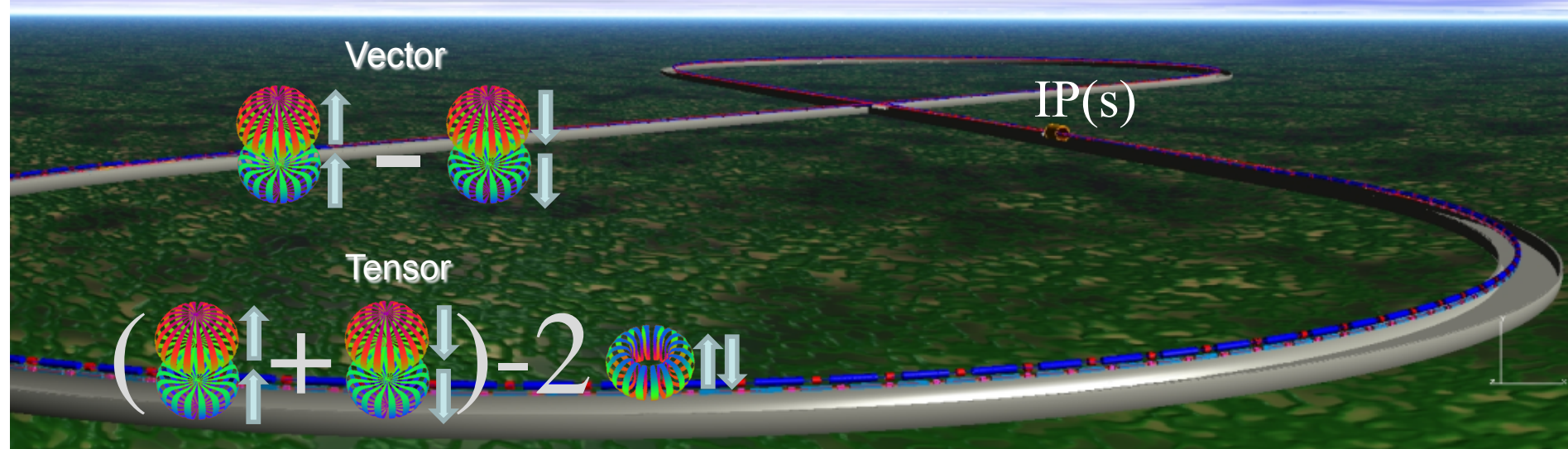


- The JLab EIC full-acceptance (IP1) detector is designed to support the physics program outlined for a generic EIC
 - Long range plan, White paper, INT report, etc
 - Particular attention paid to the more demanding exclusive- and SIDIS reactions

A detector for the EIC science program

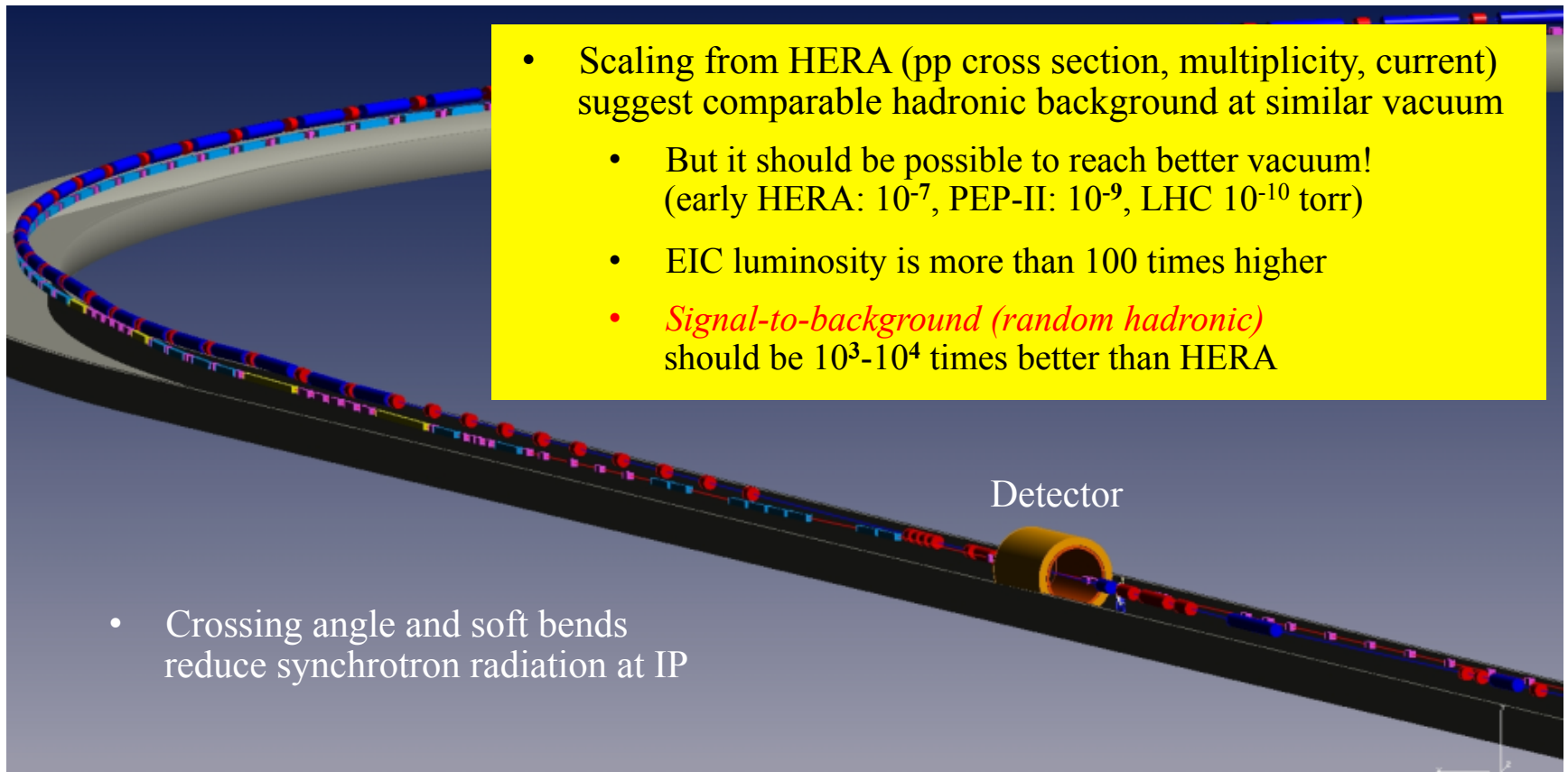
- The IP1 detector is also designed to take full advantage of unique features of the JLab EIC, and exploring physics opportunities beyond the white paper
 - Polarized deuterons possible with novel figure-8 accelerator layout
 - Capability to measure the complete final state, including all nuclear fragments
- The modular design of the IP1 central detector is also well suited for a two-detector scenario
 - Complementary, smaller IP2 detector with focus on calorimetry

→ talk by K. Hafidi

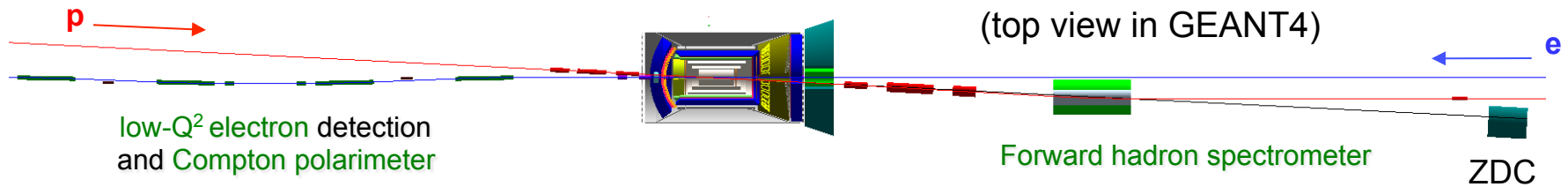


Detector locations and backgrounds

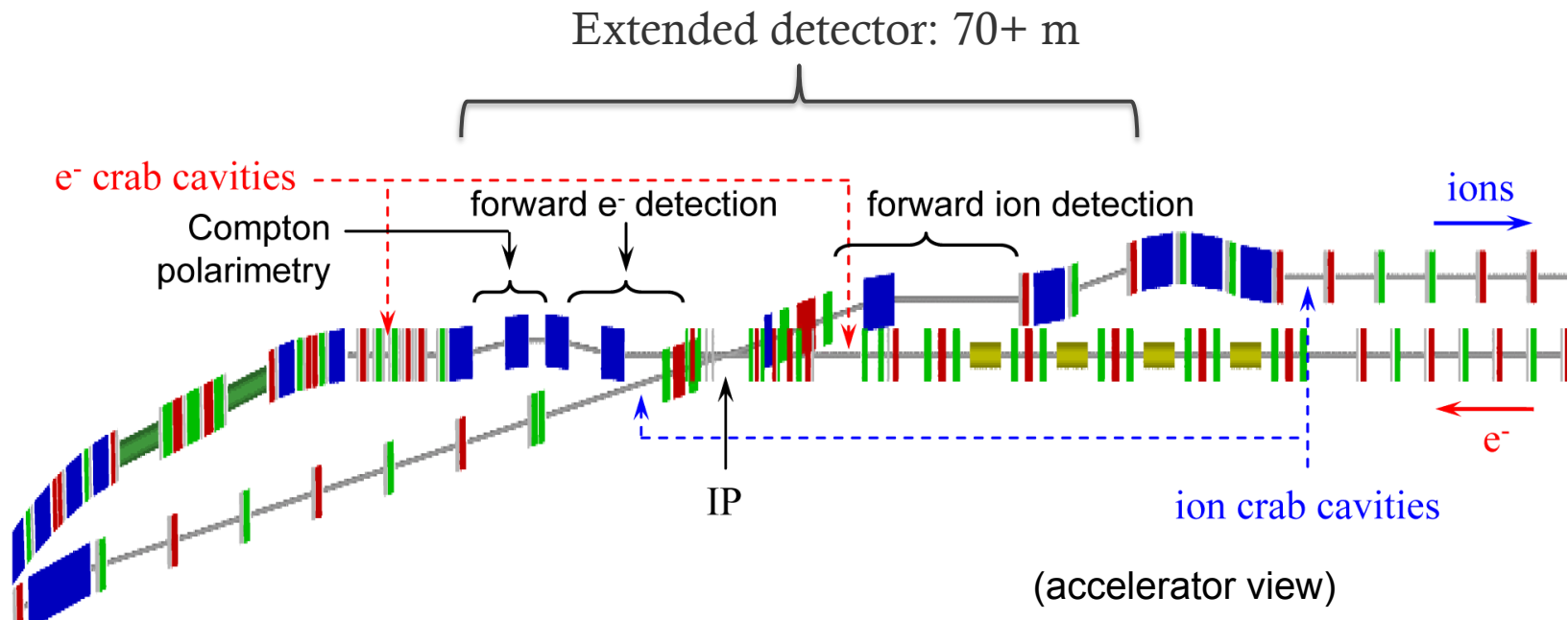
- IP locations reduce synchrotron- and hadronic backgrounds
 - *Far* from arc where electrons exit (synchrotron)
 - *Close* to arc where ions exit (hadronic) – shown below



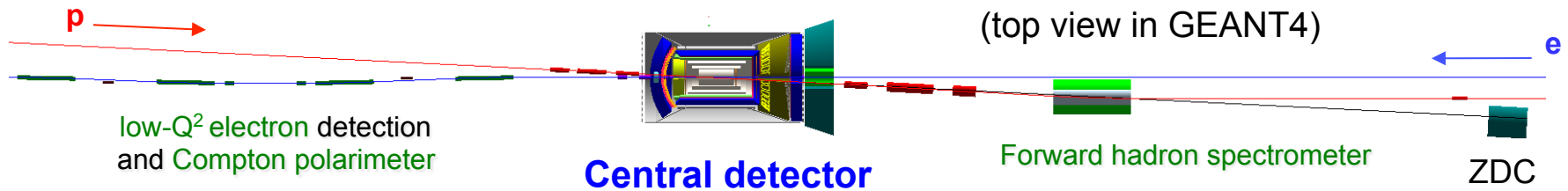
Detector and interaction region



- Integration of extended detector highest priority for JLab EIC design
 - Accelerator layout can be optimized for detector requirements



Design goals for the JLab IP1 detector



Electron Polarimetry
Low- Q^2 tagger
Lumi monitor

C

B

Forward hadron
spectrometer

A

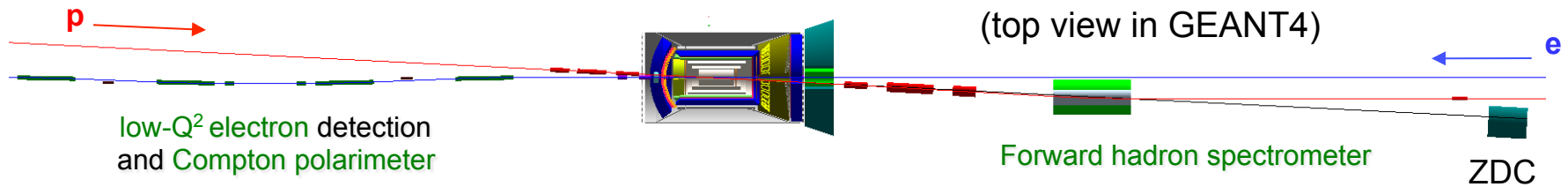
~55 mrad bend

ZDC for
neutrals

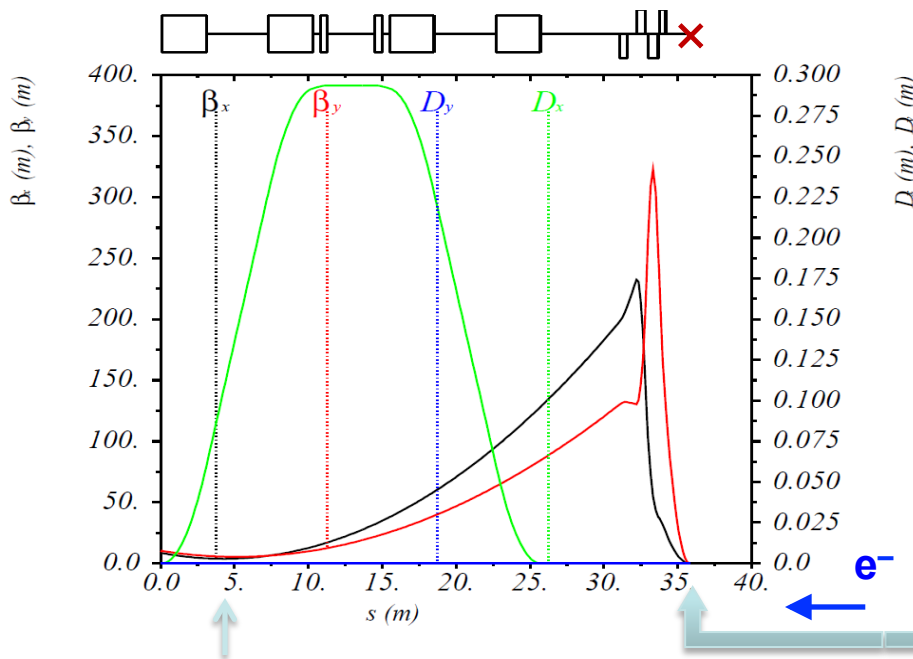
Design goals:

1. Detection/identification of complete final state
2. Spectator p_T resolution \ll Fermi momentum
3. Low- Q^2 electron tagger for photoproduction
4. Compton polarimeter with e^- and γ detection

Beam optics for extended detector

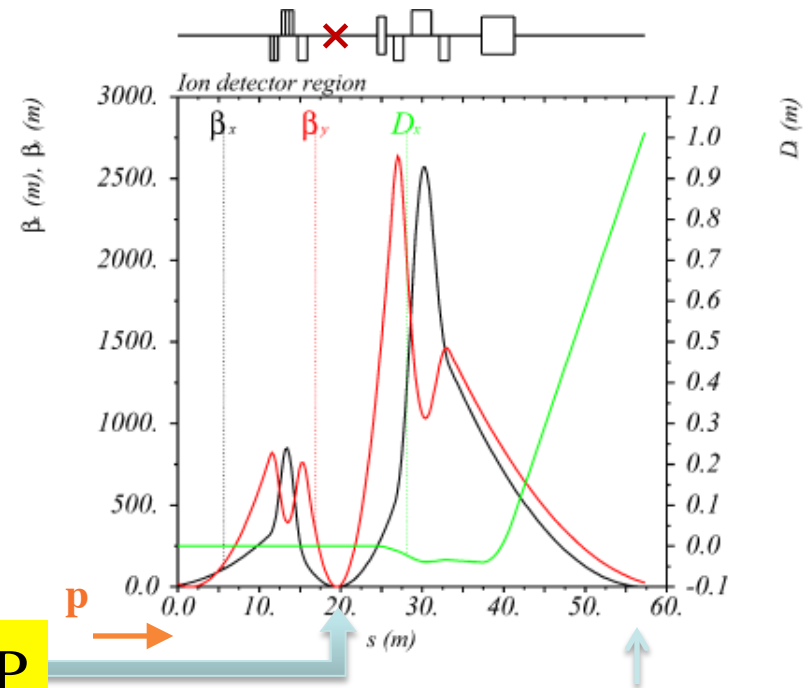


electron optics



2nd focus on Compton detectors,
dispersion for low- Q^2 tagger

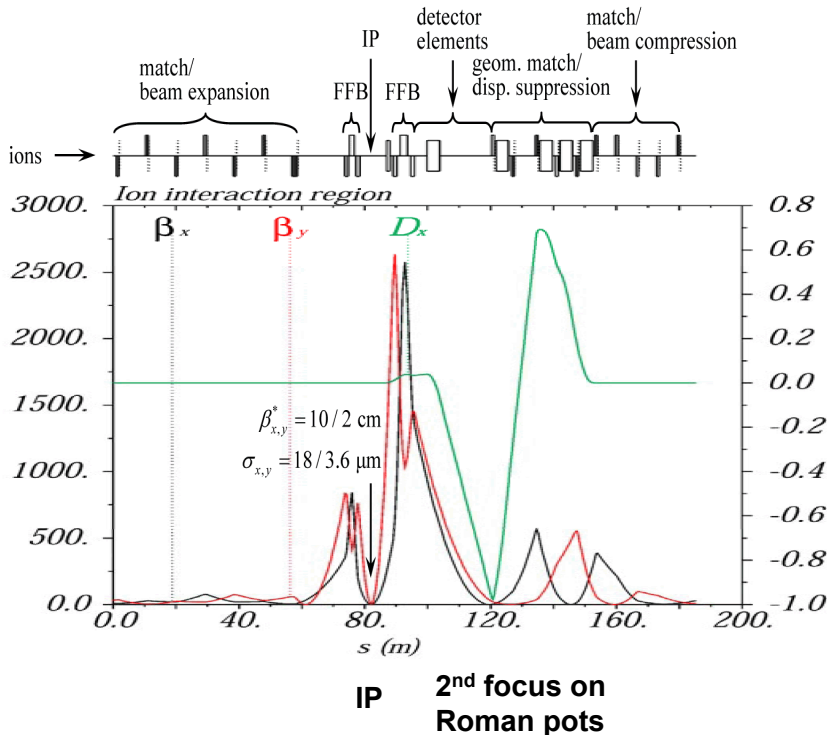
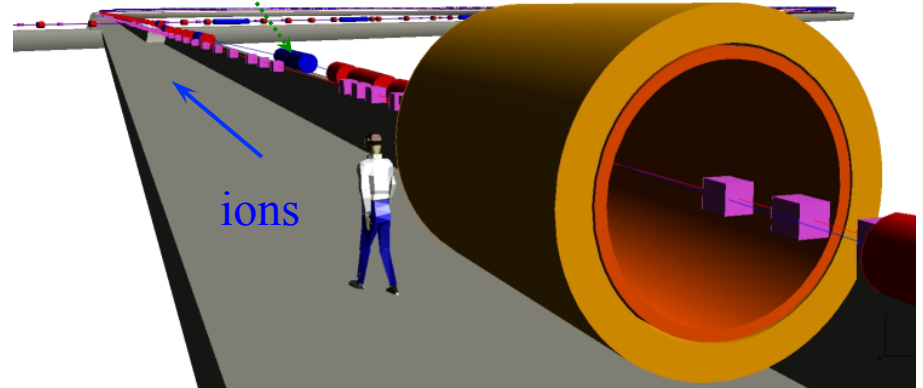
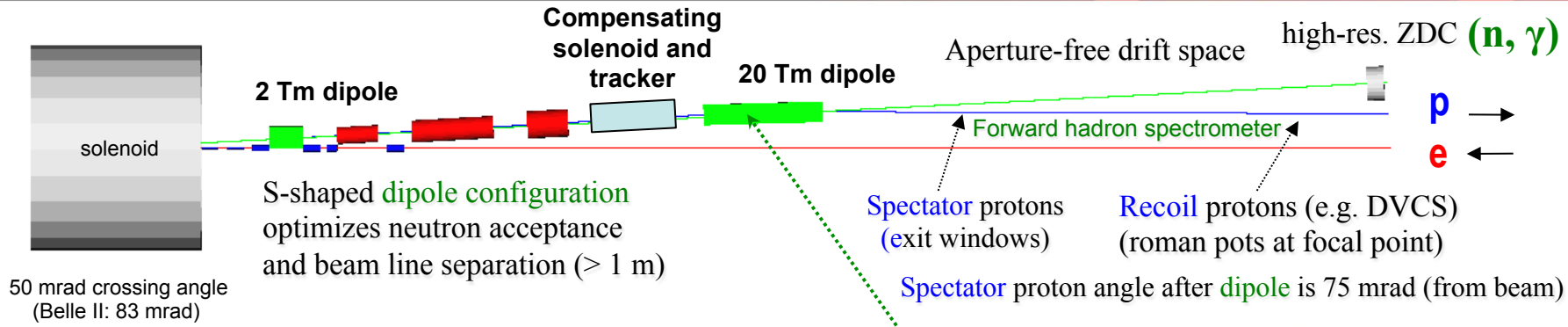
ion optics



primary focus

2nd focus and large
dispersion at Roman pots
(for recoil baryon detection)

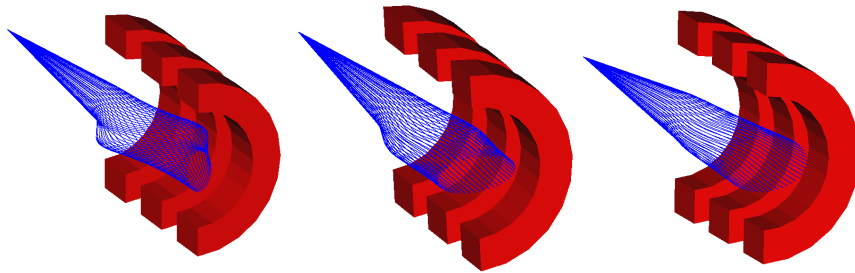
Forward hadron spectrometer



- Large 20 Tm **dipole** provides excellent resolution
- Large dispersion and small beam size at secondary focus ensure good acceptance for recoil baryons
- Large **quadrupole** apertures ($1 / \text{max beam energy}$) give good acceptance for hadronic and nuclear fragments, charged and neutral (high res. ZDC).

Fragment acceptance and resolution

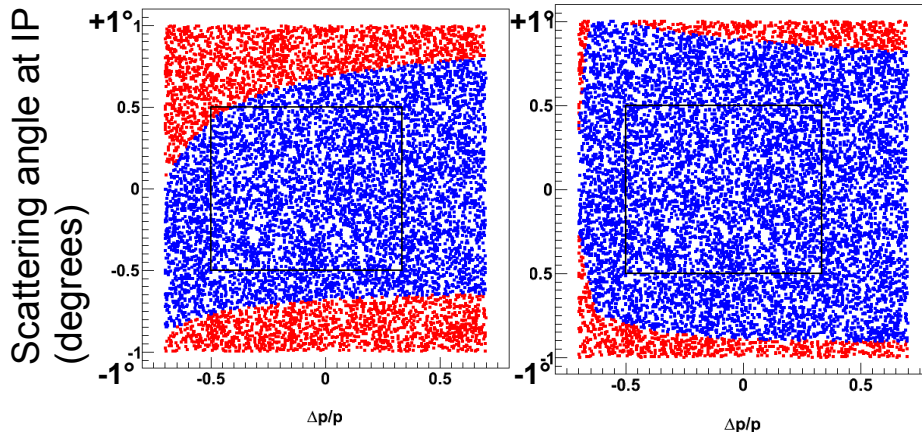
\leftarrow dp/p \rightarrow
 proton-rich fragments neutron-rich fragments
 "spectator protons from ^2H " "tritons from $N=Z$ nuclei"



Forward charged-particle acceptance

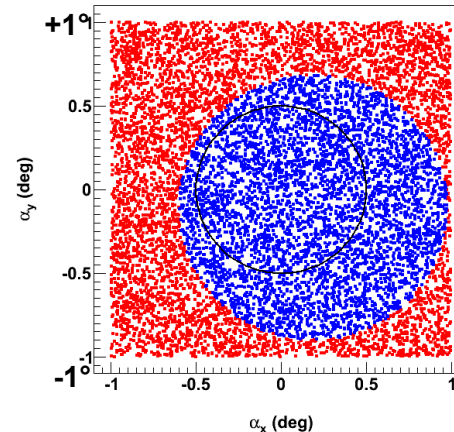
horizontal plane

vertical plane



- Full acceptance for all partonic and nuclear fragments achieved!
 - Low gradient, large aperture magnets (quadrupoles)
- Detector resolution designed to be better than intrinsic momentum and angular spread of the beam
 - Longitudinal (dp/p): *few $\times 10^{-4}$*
 - Angular (θ , for all ϕ): *$< 0.3 \text{ mrad}$*

Neutron acceptance (x and y): *25 mrad cone*

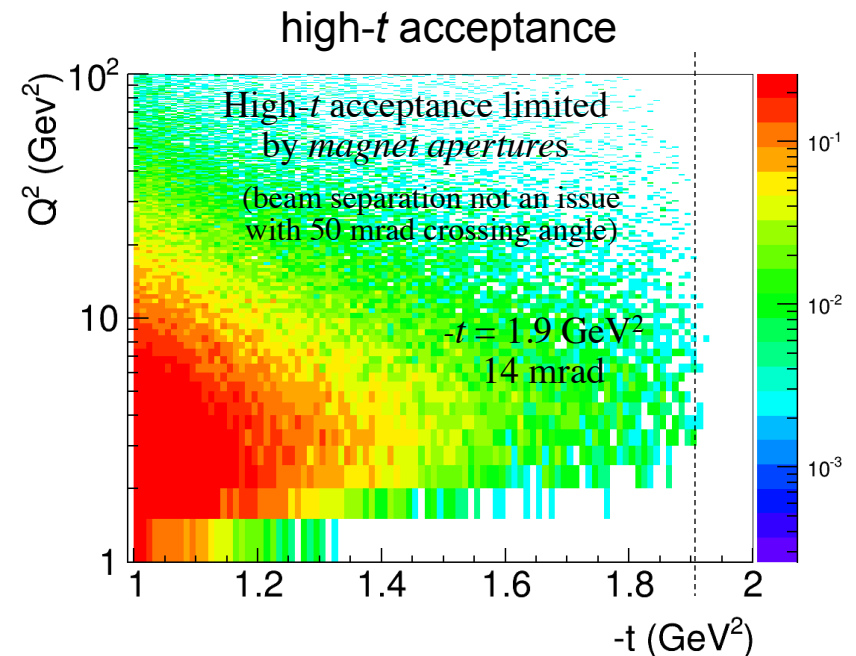
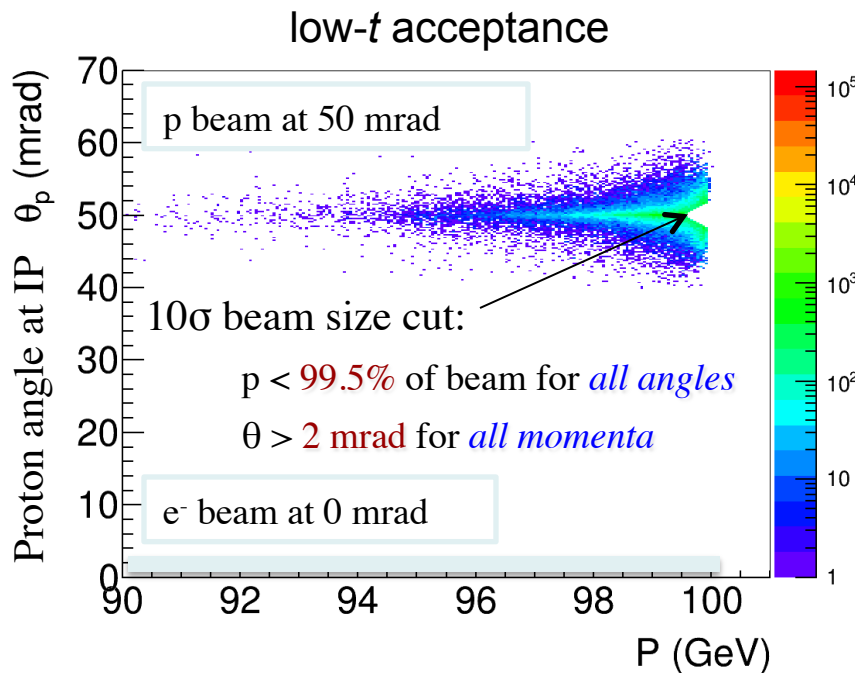


Red: Detection *before* ion quadrupoles

Blue: Detection *after* ion quadrupoles

DVCS: recoil proton acceptance

- **Kinematics:** 5 GeV e^- on 100 GeV p at a crossing angle of 50 mrad.
 - Cuts: $Q^2 > 1 \text{ GeV}^2$, $x < 0.1$, $E'_e > 1 \text{ GeV}$, recoil proton 10σ outside of beam
- **GEANT4 simulation:** tracking through magnets done using GEMC

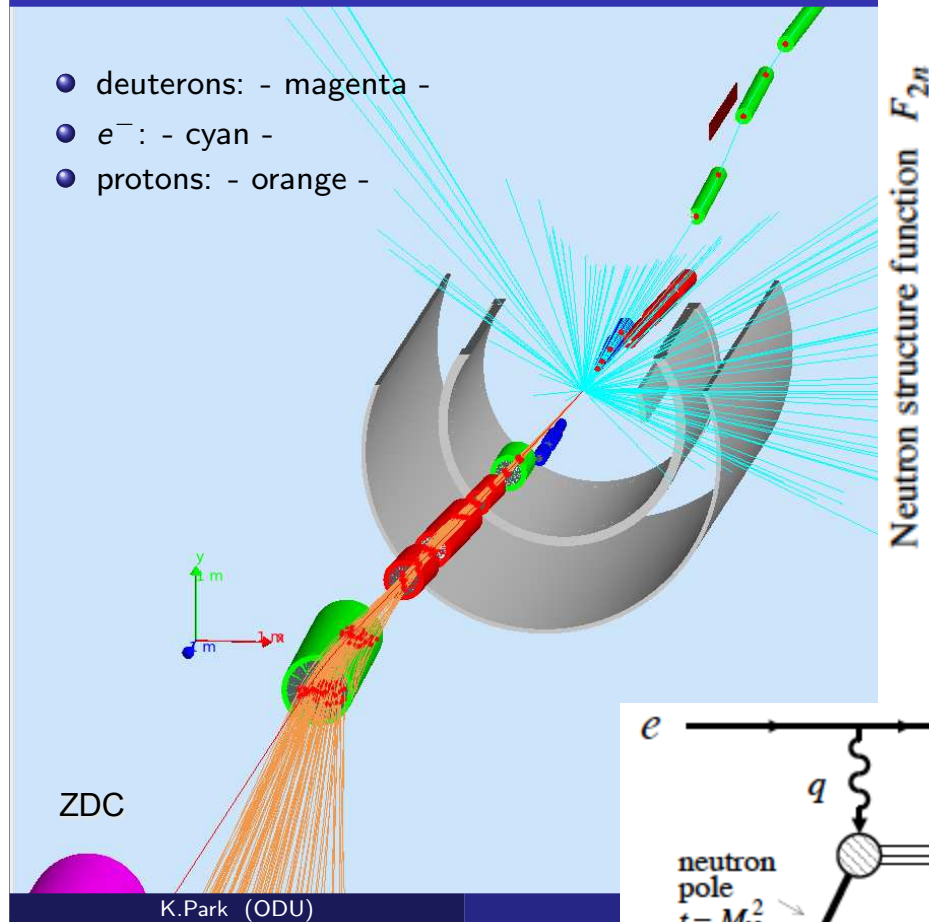


- Recoil proton angle is independent of electron beam energy: $\theta_p \approx p_T/E_p \approx \sqrt{(-t)}/E_p$
- The ion beam size (focusing, emittance, *cooling*) introduces a low- p_T ($-t$) cutoff
- Larger cone at lower E_p decreases the cutoff and make precise tracking easier

Spectator tagging: neutron structure

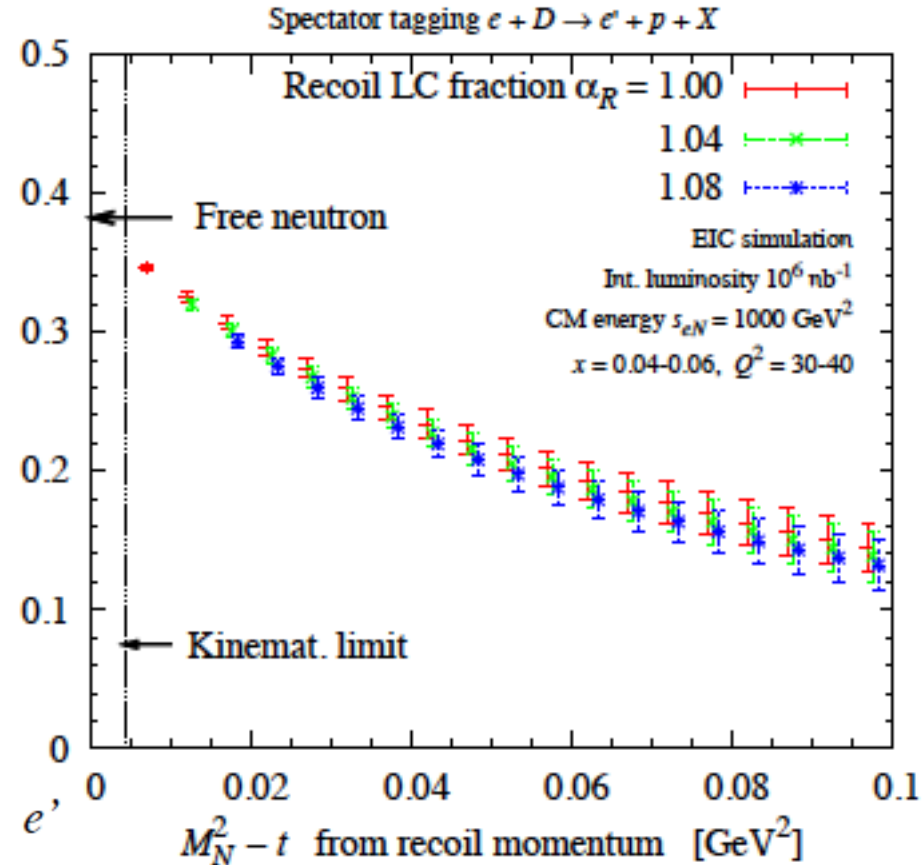
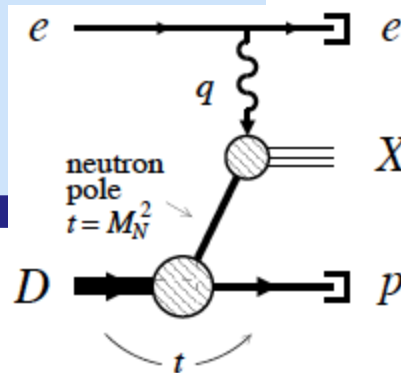
MC Simulation / GEMC

- deuterons: - magenta -
- e^- : - cyan -
- protons: - orange -



Tagged spectator protons
(no lower limit since rigidity
is different than the beam)

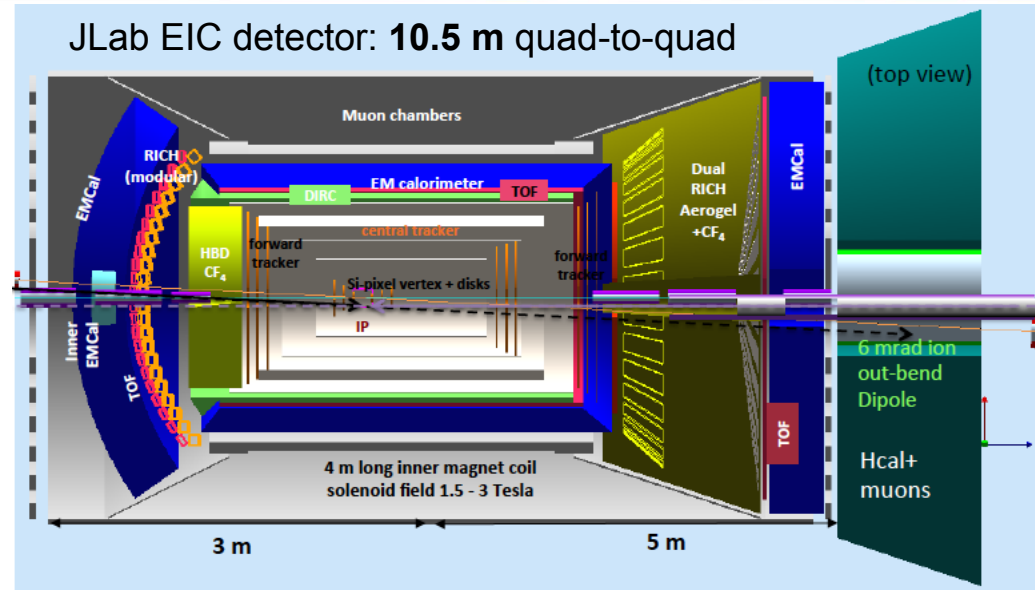
Neutron structure function F_{2n}



- On-shell extrapolation of F_{2n}
 - Requires resolution better than Fermi momentum ($< 20 \text{ MeV}/c$)
 - Resolution scales with p
 - JLab design can reach $20 \text{ MeV}/c$ even with $50 \text{ GeV}/A$ deuterium!

Central detector: design considerations

- Modular design, compatible with CLEO and BaBar 1.5 T solenoids, or a new 3 T solenoid
 - 4 m long coil, 3 m diameter
 - $FOM \sim BR^2$ for tracking in barrel
 - Central tracker resolution is not an issue if R is utilized well
- Luminosity $\sim 1 / (\text{total distance})$ between ion quadrupoles
 - Stat. error $\sim \sqrt{(\text{distance})}$
 - Important, but not at the 10% level
 - Endcap space allocation driven by physics, not accelerator
- EIC physics requires excellent PID
 - At least one detector must provide it!
 - Most challenging requirement, drives layout and size of the central detector

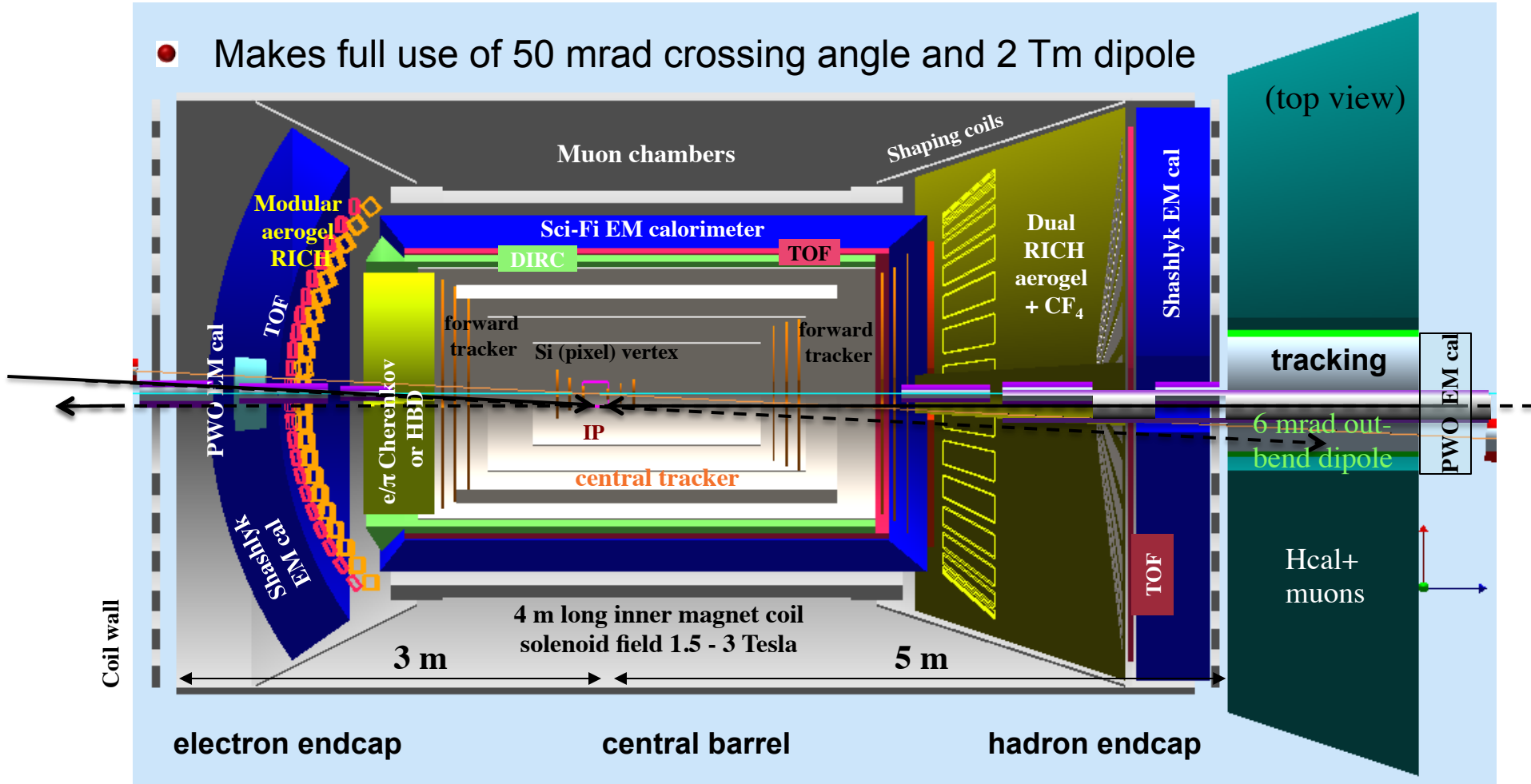


- Full-acceptance also implies good performance over full angular range
 - Particular attention paid to small-angle capabilities
- 4π Hcal (and muons) possible, but...
 - partial coverage at IP1 combined with a smaller, calorimetric IP2 detector could be more cost-effective

Central detector: overview

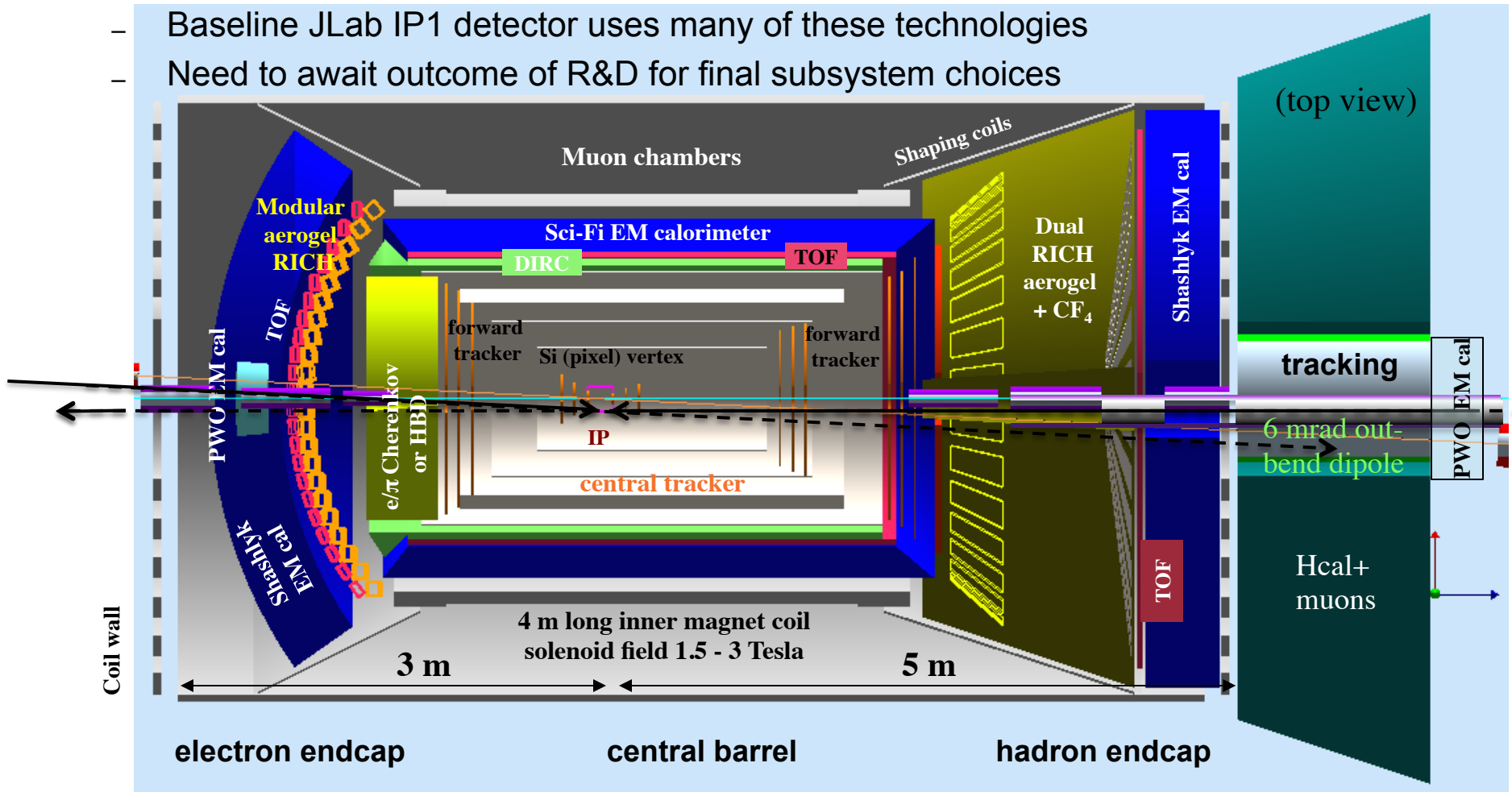
- Asymmetric IP location within solenoid and different endcaps
 - Maximizes solid angle for electron endcap
 - More space for tracking and ID of high-momentum forward-going hadrons

- Makes full use of 50 mrad crossing angle and 2 Tm dipole



Central detector: subsystems and R&D

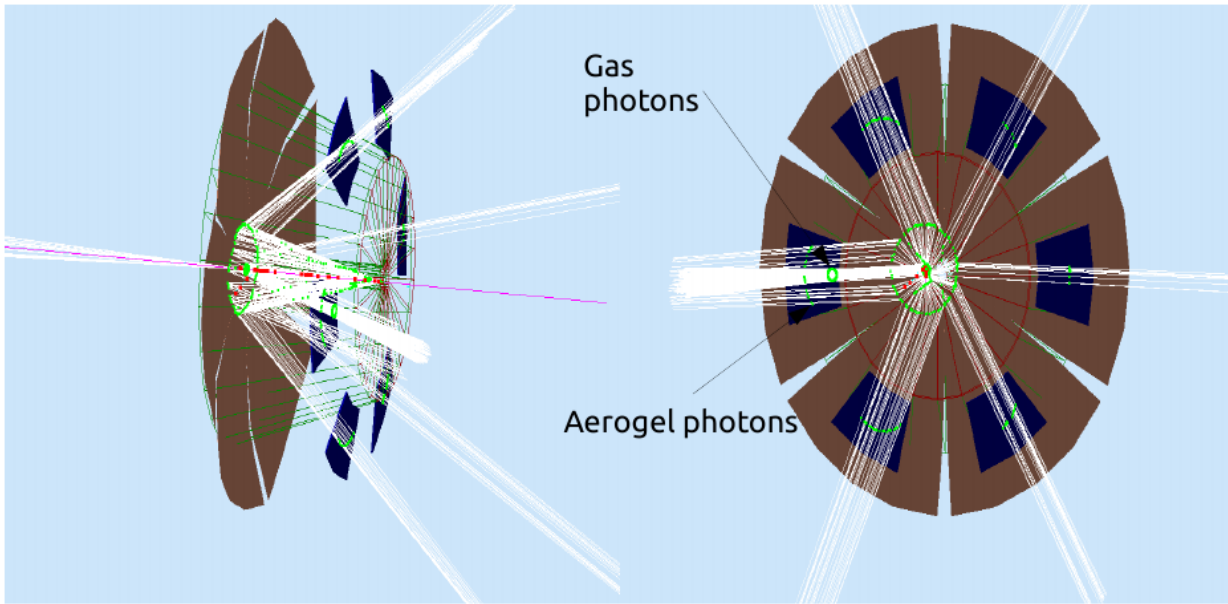
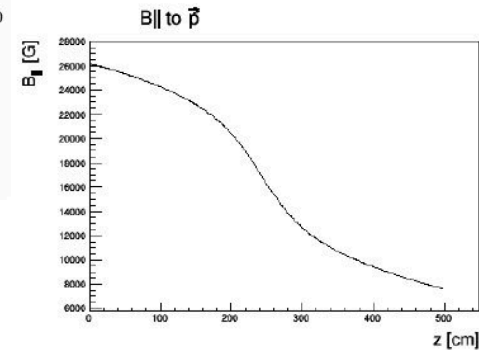
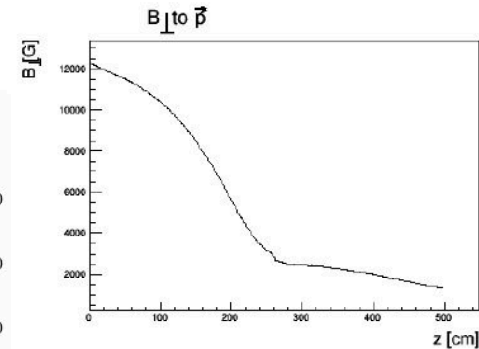
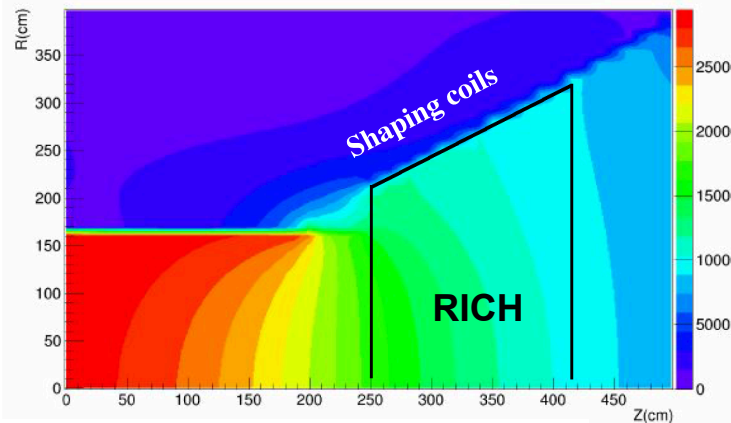
- JLab staff and users actively participate in the *Generic Detector R&D for an EIC*
 - Good opportunity for groups from JLab, BNL, and universities to work together
 - Important to continue and increase funding for this program
 - Baseline JLab IP1 detector uses many of these technologies
 - Need to await outcome of R&D for final subsystem choices



Dual-radiator RICH on hadron side

- Full momentum range (π/K up to ~ 50 GeV/c)
- Outward-reflecting mirrors
 - Move sensors away from the beam
 - UV photons from CF_4 gas do not go through aerogel
- Smearing from field perpendicular to the track can be suppressed by active shaping

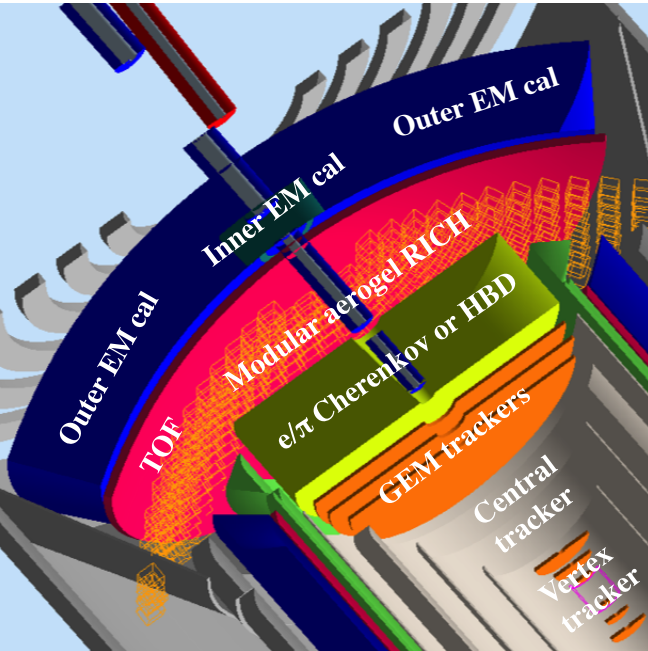
Hadron-side field in the IP1 solenoid



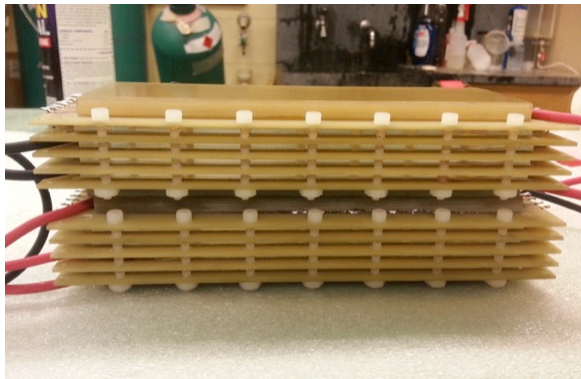
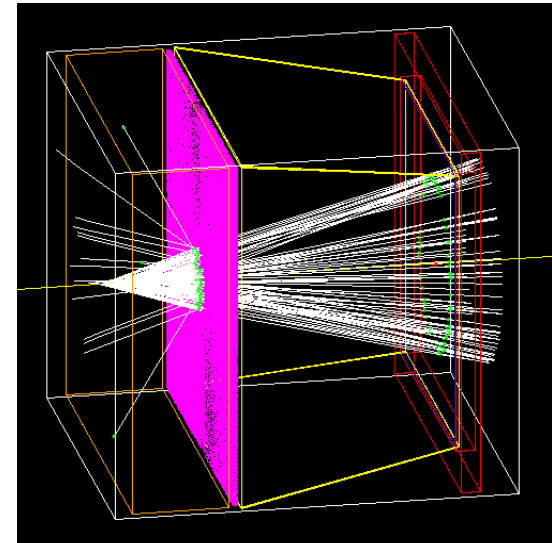
- 3D focusing ensures small sensor area (blue)
- Dual-radiator RICH R&D is pursued by the EIC PID consortium (eRD14)

→ talk by Z.W. Zhao

PID on the electron side



- Significant pion background up to a few (4-5) GeV/c
- Should supplement EM cal. for reliable identification of scattered electron
 - Threshold Cherenkov, or
 - Hadron-Blind Detector?
- Asymmetric layout increases solid angle covered by electron endcap

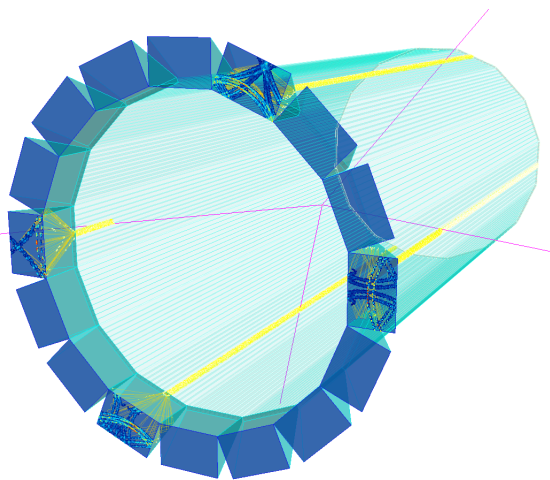
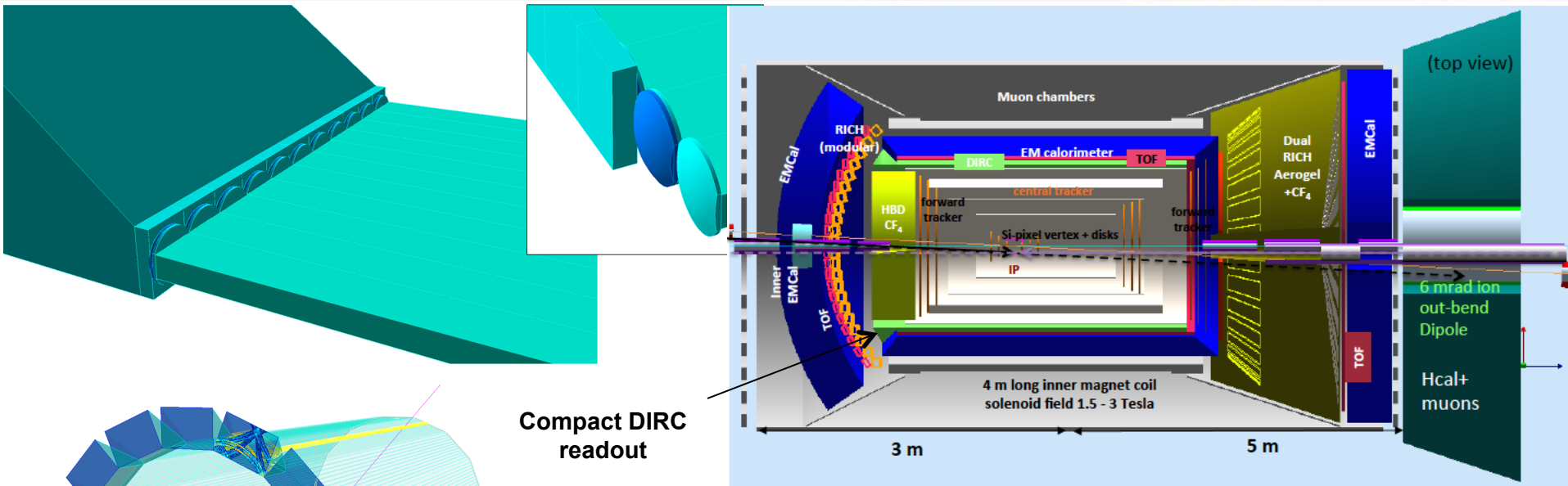


- High-resolution mRPC 10-20 ps TOF (eRD14)
 - TOF in both endcaps and barrel important for bunch identification (30-50 ps would be ok)
 - Relative timing (t_0 from identified electrons)
- Projective, modular aerogel RICH (eRD14)
 - π/K separation up to ~ 10 GeV/c
 - Good range since hadron ID above typical electron beam energies is not needed here
 - Endcap area smaller than barrel, but Important to reduce sensor costs (LAPPDs?)

→ talk by I. Choi

→ talk by Z.W. Zhao

Hadron ID in the central barrel



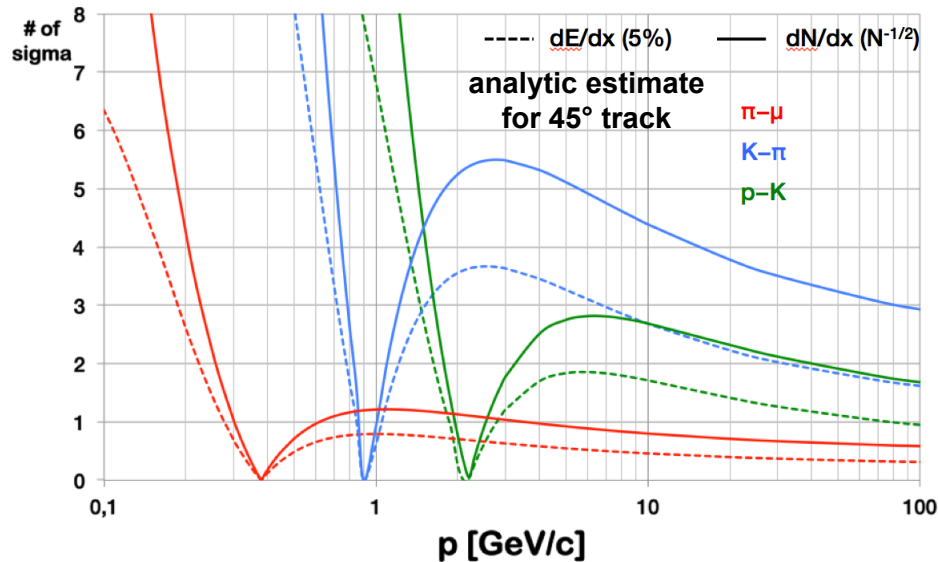
→ talk by G. Kalicy

- A DIRC is a radially compact (2 cm) Cherenkov detector
 - Used at BaBar, planned for Belle II, GlueX
- EIC R&D (eRD14) show that performance can be significantly improved by using focusing lens optics
 - p/K : 10 GeV/c, π/K : 6 GeV/c, e/π : 1.8 GeV/c
 - Very compact readout “camera” with small sensor area
- Additional PID from TOF and, possibly, central tracker

Central tracker with PID beyond dE/dx?

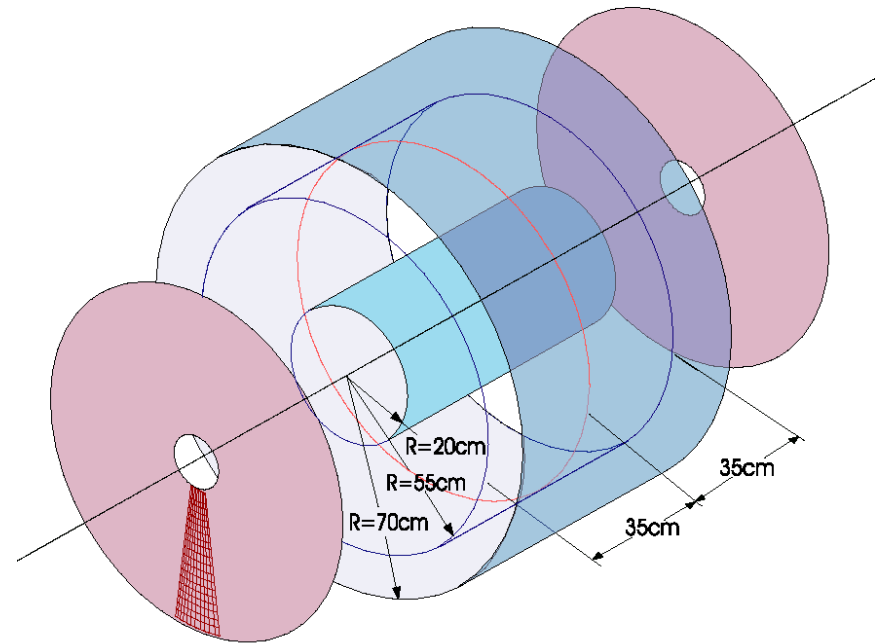
Ultra-low mass, He-filled, cluster counting drift chambers

Particle Separation (dE/dx vs dN/dx)



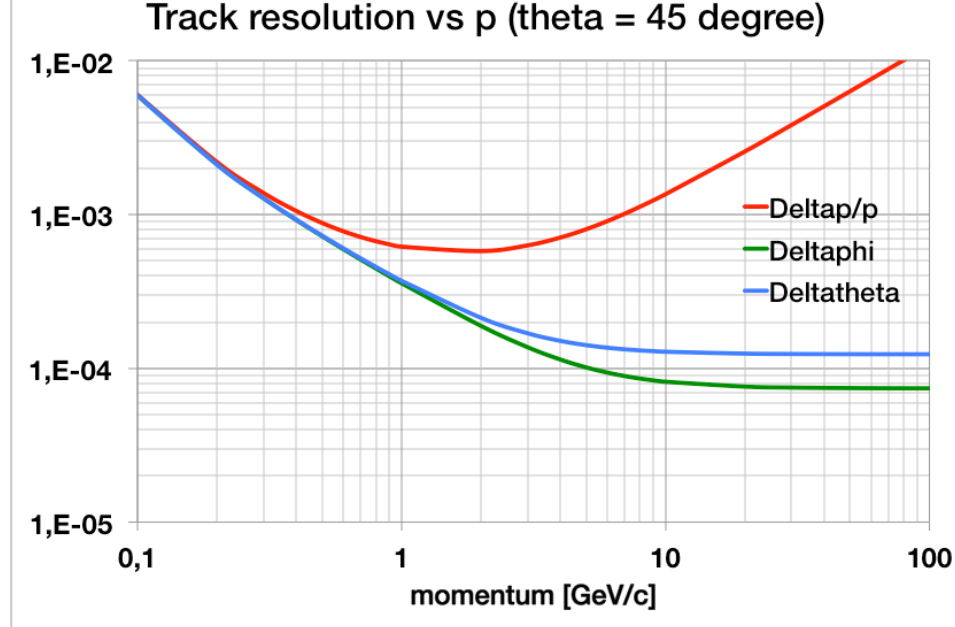
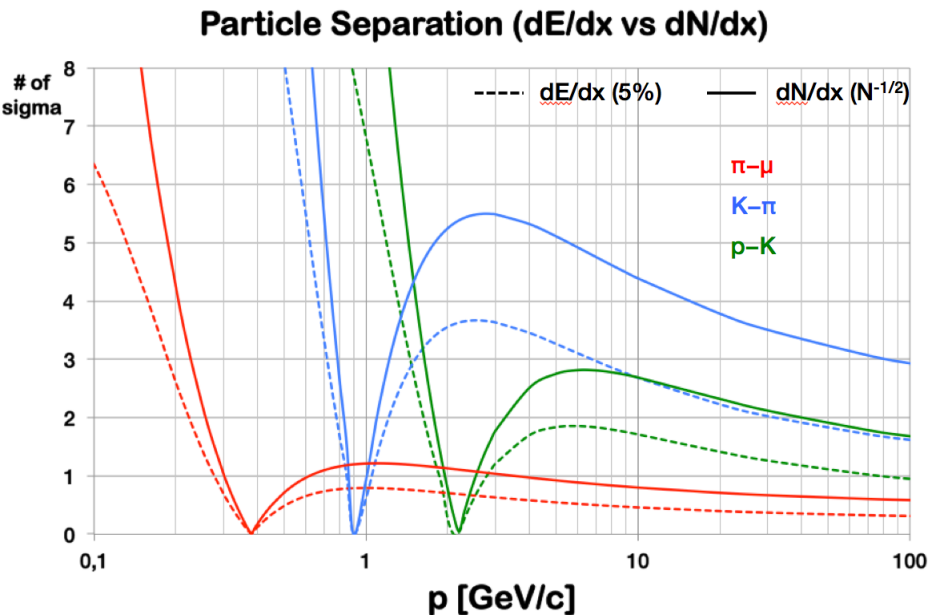
- Based on KLOE (INFN) and proposed mu2e and ILC 4th concept chambers
 - Precise tracking of low-momentum e^-
- Cluster counting (dN/dx) gives a very significant improvement over dE/dx
 - Hadron ID complementary to Cherenkov detectors: π/K separation better than K/p

TPC and HBD sharing gas volume



- Proposed for the PHENIX hadron-blind detector (HBD)
 - e/π ID up to 4 GeV/c
- R&D pursued for the PHENIX upgrade and within the eRD6 tracking consortium
 - Bench tests suggest concept is possible

Low-mass, cluster-counting tracker

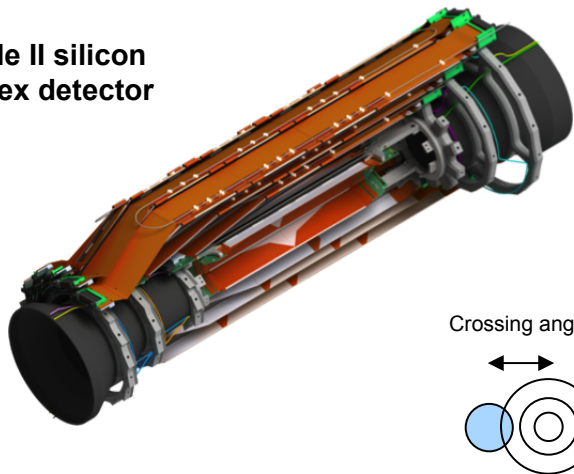


- Analytical performance estimates for a low-mass tracker in a 3 T field
 - JLab IP1 geometry: 0.2 m inner- and 1.1 m outer radius (could also be adapted for IP2)
 - Design performed by the INFN-Lecce group
- He-filled chamber with low-mass, all-stereo wires
 - Minimal multiple scattering and good angular resolution
 - Does not require very flat central solenoid field (easier to integrate with dual-radiator RICH)
- Slow He gas and a readout with high-frequency sampling make it possible to measure the arrival of each cluster at the wire, greatly improving hadron ID
 - Poor resolution at crossover points at low p where the dE/dx (and dN/dx) for each pair is equal

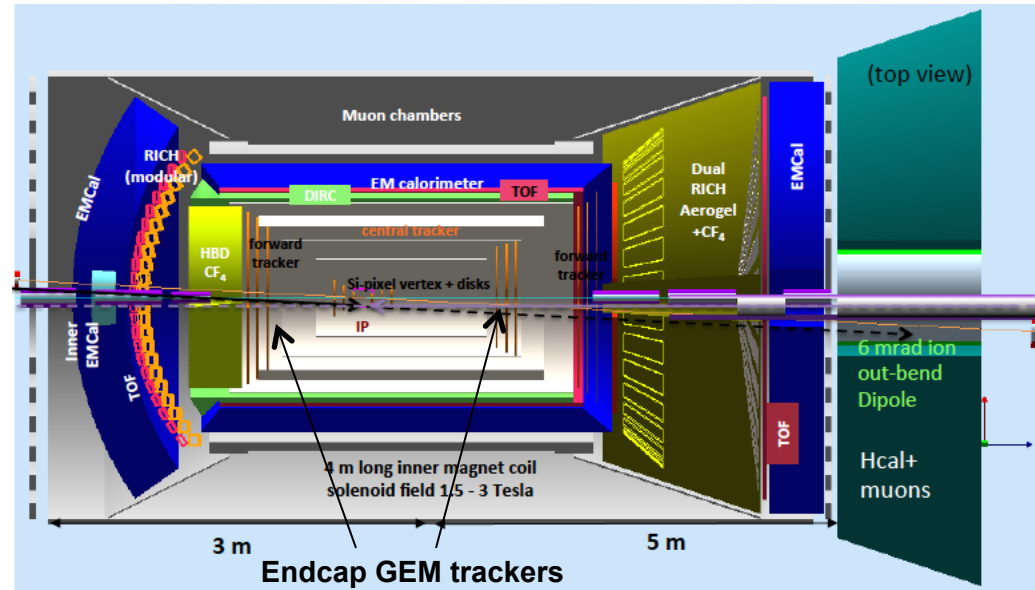
Vertex and endcap trackers

- A silicon-pixel vertex detector is important for heavy flavor physics
 - Several technology options
 - Important to await Belle II experience with new DEPFET-based pixel SVD

Belle II silicon vertex detector

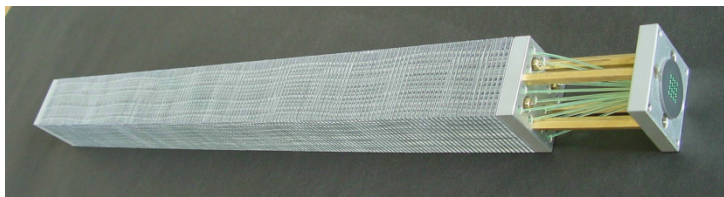


- Due to a large crossing angle (50 mrad) and dipole, silicon trackers are only needed in the vicinity of the vertex
 - Crossing shifts zone of poor resolution along solenoid axis into periphery
 - 2 Tm dipole between solenoid and ion quads further improves resolution



- Baseline solution for both endcap trackers are micropattern gas detectors (eRD6)
 - Similar to GEMs developed for SoLID
 - Micromegas could also be used in barrel
- An interesting option would be to replace or combine the ion-side GEM with a TRD
 - e/π ID over 2-100 GeV/c range is ideal for background suppression in J/ψ decays or detecting backward-scattered electrons

Electromagnetic calorimetry

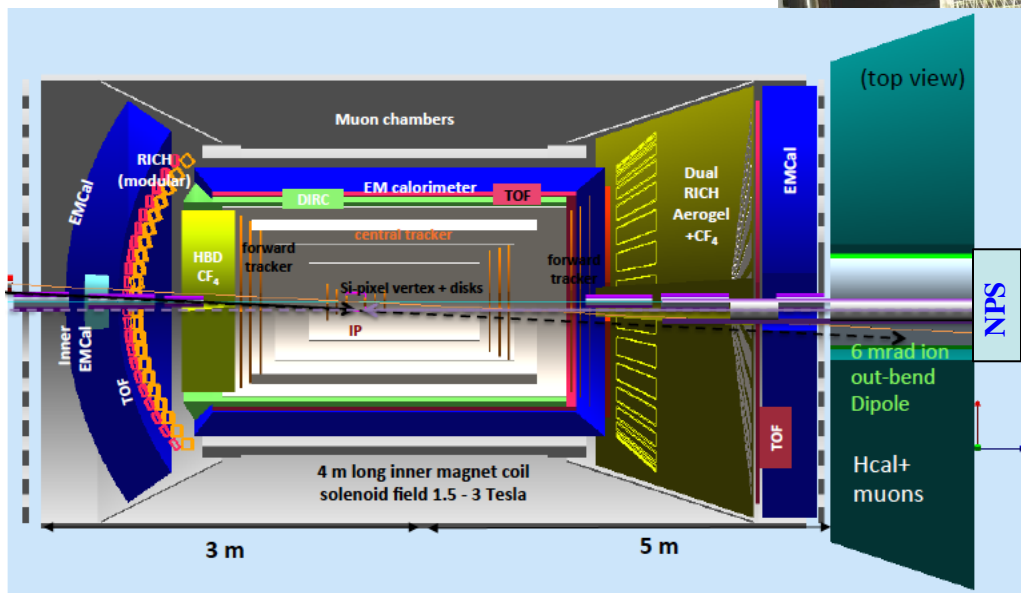


COMPASS Shashlik module
SoLID will use similar modules

Shashlyk and PWO_4 R&D
is carried out by the eRD1
calorimetry consortium



JLab NPS PWO_4
crystals
can be re-used
on hadron side

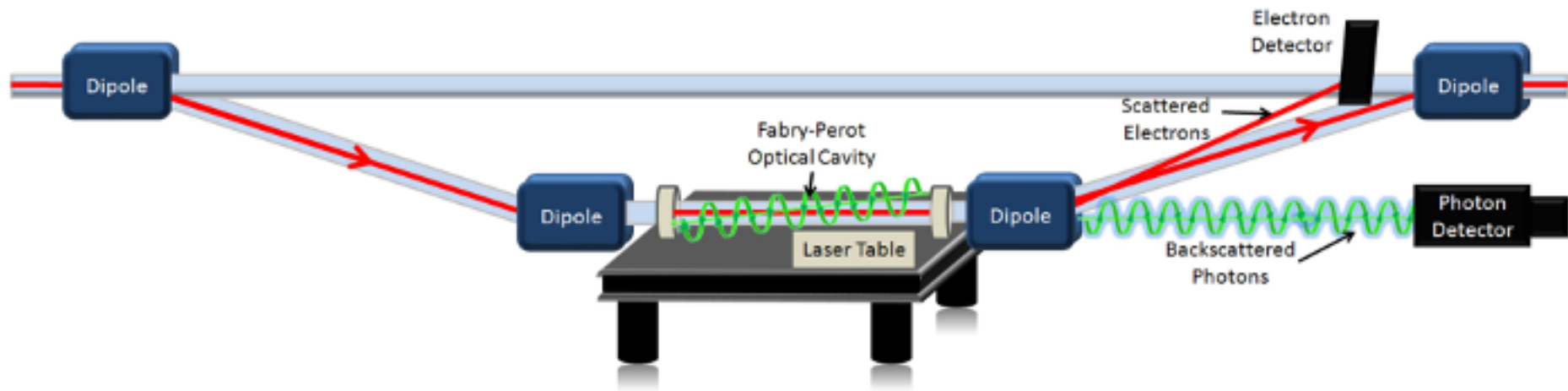


- As in CLAS, the endcap EM cals are divided into inner and outer parts.
 - Outer: Shashlyk
 - Inner: PWO_4
- Outer calorimeter provides e/π ID and photon detection
- The high-resolution ($2\%/\sqrt{E}$) inner calorimeter also provides energy information for electron momentum reconstruction where the tracking resolution is poor
- Compact scintillating fiber EM cal in central barrel
 - GlueX BCAL (lead Sci-Fi) is a good option
 - Tungsten powder (eRD1) could be an alternative, although construction is very labor intensive
 - Pre-shower functionality (γ/π^0 separation for DVCS) is important in both barrel and endcaps

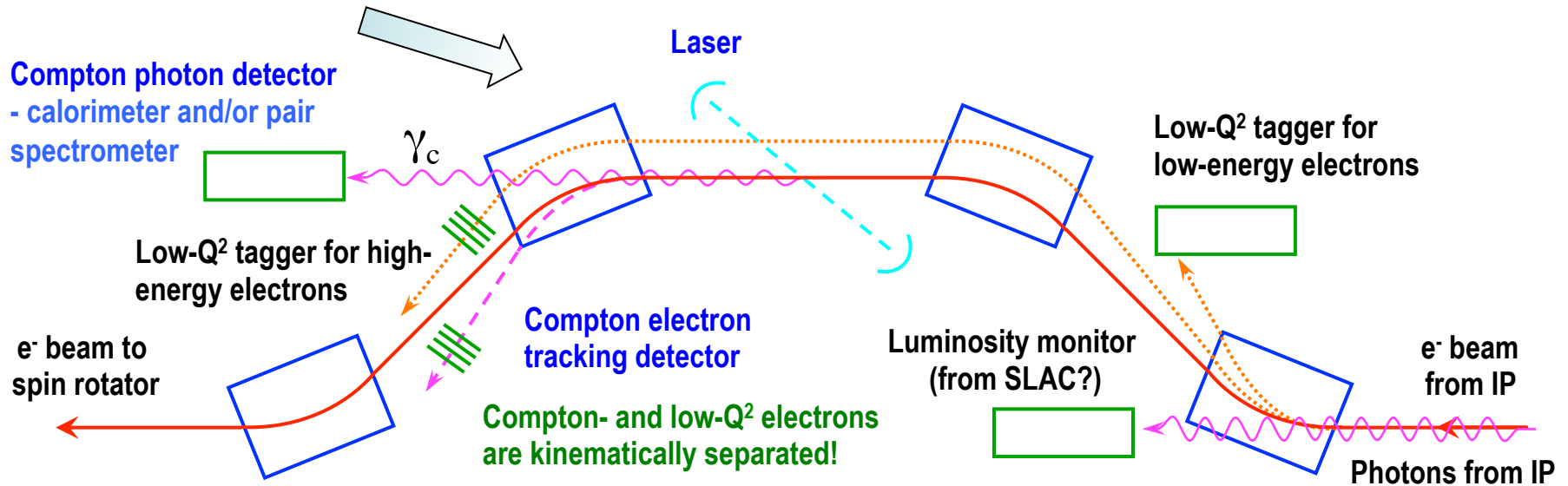
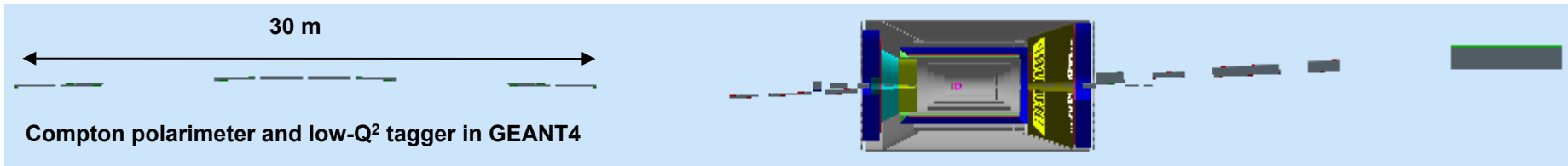
Compton polarimetry

- Experience from HERA: uncertainty $> 1\%$
 - Limited to detection of Compton photon only
 - Accelerator limitations (non-colliding bunches)
- Experience from JLab and SLAC
 - SLD at SLAC reached 0.5% detecting the Compton electron
 - Compton polarimeters in Halls A and C at JLab reach $< 1\%$ detecting both the photon *and* the electron for cross check

Laser at chicane center ensures that polarization is identical to IP



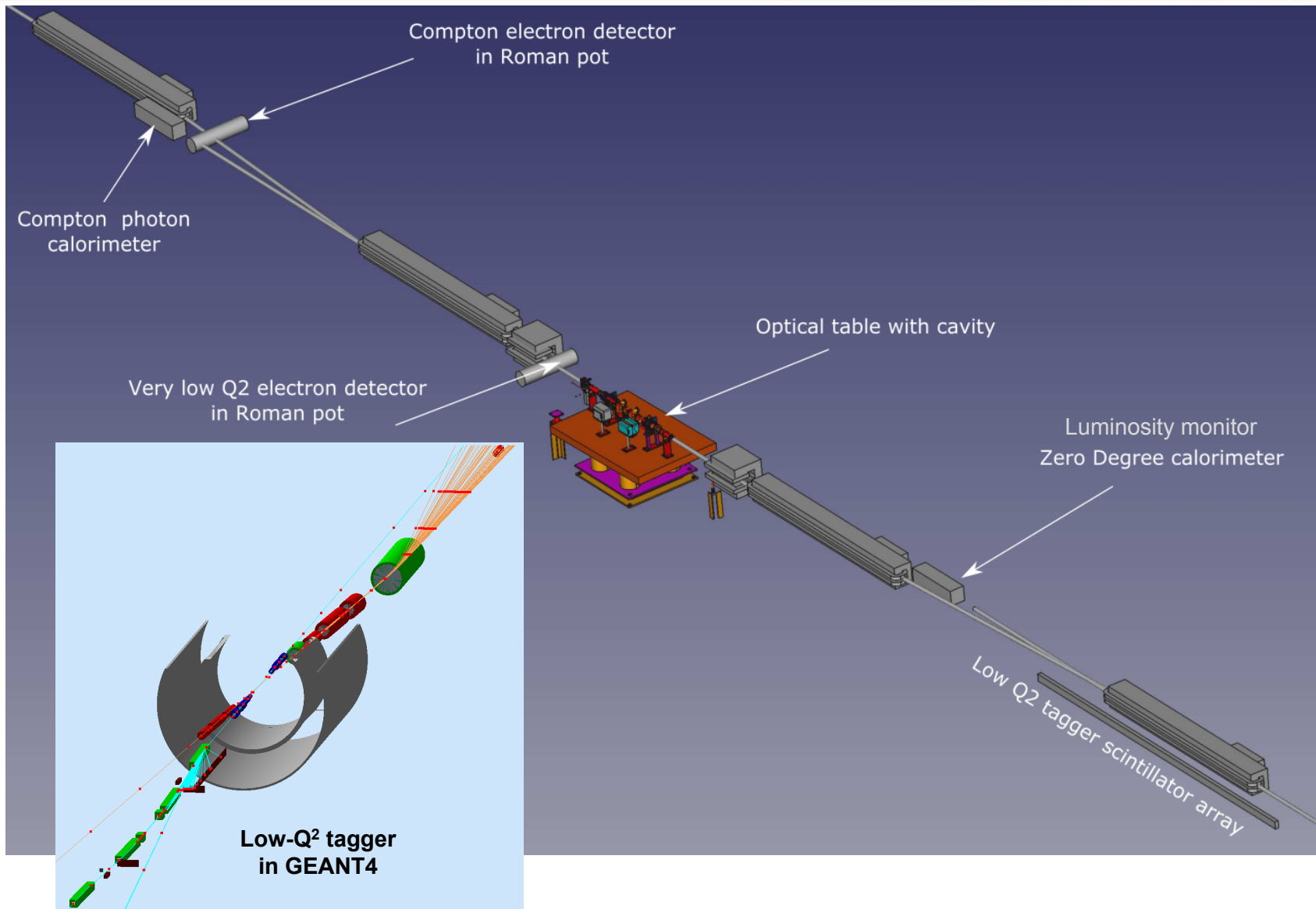
Polarimeter and low- Q^2 tagger



- IP1 will have a large, integrated chicane
 - Detection of both Compton electron and photon
 - Low synchrotron backgrounds
 - Low- Q^2 tagger for photoproduction
 - Luminosity monitor (from PEP-II?)

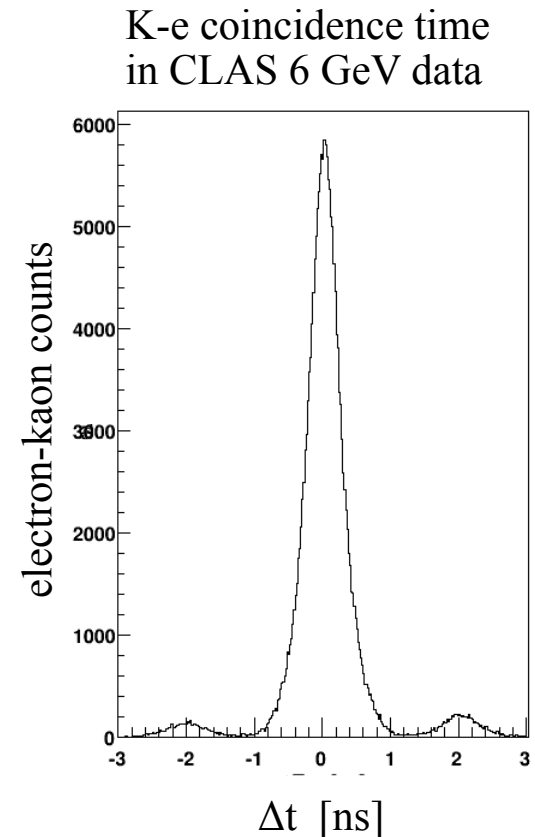
→ talk by J. Hoskins

Compton/low- Q^2 chicane layout



Bunch spacing and identification

- Detectors (CLAS, BaBar, etc) at machines with high bunch crossing rates have not had problems in associating particle tracks with a specific bunch.
 - Having more bunches *lowers* the average number of collisions per crossing
- Example: CLAS detector at JLab 6 GeV
 - 2 ns bunch spacing (500 MHz rep. rate)
 - 0.2 ns TOF resolution (0.5 ns FWHM)
 - The figure shows time matching of kaons in CLAS with electrons in the (low- Q^2) tagger, in turn matched to the accelerator RF signal
 - The 2 ns bunch structure is clearly resolved*
 - CLAS12 aims at a TOF resolution of 80 ps
- The bunch spacing in the MEIC is similar to CLAS and most e^+e^- colliders
 - PEP-II/BaBar, KEKB/Belle: **8 ns** (*1/4 of buckets full*)
 - Super KEKB/Belle II: **4 ns** (*2 ns with all RF buckets full*)
 - **JLab EIC: 2 ns** [476 MHz – as in PEP-II]
 - CERN Linear Collider (CLIC): **0.5 ns** [2 GHz]



Asynchronous triggering

- The JLab EIC will use a “smart” asynchronous trigger and pipelined electronics
 - The L1 rate is expected to be comparable to GlueX (200 kHz)
Low- Q^2 (photoproduction) events will be pre-scaled
 - Simple tracking at L2 will suppress random background
Already planned for CLAS12
- Data-driven, asynchronous triggers are well-established
 - If the number of collisions of interest per bunch crossing is $\ll 1$, synchronizing the trigger to each RF clock cycle becomes inefficient
 - Sampling rate requirements for the pipelined electronics depend on signal properties and backgrounds, not the bunch crossing frequency
JLab 12 GeV uses flash ADCs with 250 MHz (4 ns) sampling
 - When a trigger condition is fulfilled (e.g., e^- found), memory buffers are written to disk or passed to L3 (at PANDA signals will go directly to L3)
 - Correlations with the RF are made offline
 - T0 can be obtained from tracking high- β particles (e.g., electrons in CLAS)

Summary and Outlook

- The JLab full-acceptance (IP1) detector has been designed to support the full physics program of the EIC
 - Easily adaptable to a two-detector scenario
- The extended IP1 detector has been fully integrated with the accelerator
 - Unprecedented small-angle acceptance and resolution
 - High-precision electron polarimetry and low- Q^2 tagging
- The central detector offers great performance, in particular for the more demanding exclusive and semi-inclusive processes
 - Excellent PID
 - Doubly asymmetric layout optimizes available space
 - Need to await R&D results for final decision on all subsystems
- Lots of opportunities for collaboration on detector design and R&D
 - Generic Detector R&D for an EIC program important!